

On the M_T scaling of dilepton spectra in high energy heavy ion collisions

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Abstract

The so-called M_T scaling for dilepton spectra at RHIC energies is examined. It is seen that a proper accounting of the complete set of dilepton producing processes forces us to abandon the proposed scaling around $M_T = 2.6$ GeV, which has been put forward as a possible signature of the presence of quark-matter. Any substantial transverse expansion in the QGP phase itself will also offset this scaling behaviour. The rates of lepton pair production are time-integrated in Bjorken hydrodynamics and the different sources are compared against each other.

1 INTRODUCTION

Quantum Chromodynamics is by now firmly established as the theory of strong interaction. One of its most spectacular predictions, namely the formation of quark-gluon plasma (QGP) will be experimentally investigated at the Relativistic Heavy Ion Collider under construction at Brookhaven and the proposed Large Hadron Collider at CERN. The QGP likely to be produced in these experiments is expected to survive only for a brief duration of at the most a few fm/c, and a host of suggestions have been put forward to verify its formation and subsequent evolution. The early theoretical descriptions [1] have been tremendously successful in generating activity and ideas. Recently, approaches have been put forward to treat certain aspects of the nucleus-nucleus collisions on a microscopic level [2]. If the QCD plasma is formed in such collisions and if QCD as a theory admits a first order phase transition, the system might further pass through a phase mixture of quarks, gluons and hadrons [3]. Subsequently, the hadrons lose thermal contact and free-stream towards the detectors.

The space-time evolution of this matter could be reflected by the yield of high energy photons and dileptons. These electromagnetic probes are considered reliable because their production rates are very strongly increasing functions of the temperature (local energy density) and they escape from the system without attenuation after they are produced.

These endearing aspects of photons and dileptons have led to a thorough examination of the processes affecting their production. Thus, for example, a

study of photon–yielding processes in hadrons and QGP led to the surprising finding that the rate of emission of photons at a given temperature is phase independent [4]. This necessitated much higher initial temperatures for the QGP phase for cleaner signals to emerge [5]. Such high initial temperatures may perhaps be achieved at the RHIC or the LHC [2].

For a long time the dileptons having large invariant masses were believed to have their origin in the process $q\bar{q} \rightarrow l\bar{l}$ for the plasma and in the process $\pi^+\pi^- \rightarrow l\bar{l}$ for the hadronic matter. As the pion-annihilation process thus envisaged is dominated by the ρ meson, it immediately led to the suggestion that dileptons having their invariant masses larger than that for the ρ meson would have their origin predominantly in the quark matter [6].

These early expectations need to be re-examined in the light of recent findings [7], where for the first time a complete list of light mesons was used to obtain the rates for dilepton yield in a hot hadronic matter. An important consequence of the quoted work is that the inclusion of vector decays and two-body reactions lead to an enhancement of the rate for dilepton production by a factor of 10–50, compared to the situation when only pion annihilation is considered, up to an invariant mass $M \approx 3$ GeV. An immediate outcome of this result is that the safe window for detecting dileptons from the plasma is now pushed up to a region where Drell–Yan dileptons are no longer negligible.

These results also force us to abandon the so-called M_T scaling for dilepton spectra around $M_T = 2.6$ GeV, which has been proposed as a signature of the presence of quark-matter [8]. The transverse mass scaling of the lepton

spectrum in high energy heavy ion collisions will occur for an ensemble of massless quarks in thermal equilibrium, undergoing longitudinal expansion only. These conditions ensure that the only scale in the problem is the temperature, T . Then $dN/dM^2 dy d^2q_T$ is a function of M_T only. However, this feature does not persist in the hadronic sector where the timelike electromagnetic form factors explicitly break the scaling law. Nevertheless, there has been recent hope that the M_T scaling in the pure QCD sector could still be observed in the net signal [8]. As we shall see, this possibility hinges on the dilepton yielding processes in the nonperturbative regime being approximated by $\pi^+\pi^- \rightarrow l\bar{l}$, which has a negligible contribution beyond $M \geq 1$ GeV. Unfortunately, the M_T scaling is not observed even for a purely longitudinal expansion of the system once a full set of dilepton producing rates in hadronic matter are accounted for. Also, we mention the unavoidable complications resulting from transverse expansion [9]. Even in the absence of the arguments made in this paper, this would seriously challenge the extraction of a clean signal.

In this paper, we consider the impact of a larger set of lepton pair emitting processes on lepton spectra and on the hypothesis of M_T scaling.

2 FORMULATION

The dilepton yield calculations for collisions involving two nuclei have routinely been carried on in the following manner. First, the Drell-Yan contribution is either calculated or estimated by scaling the pp spectrum by

an appropriate power of A . A second contribution is obtained by integrating the thermal emission rate over the space-time history of the collision [6]. We assume that a thermalized quark-gluon plasma is formed at some initial temperature T_0 at initial proper time τ_0 . This plasma is then believed to expand and cool. Soon it reaches the critical temperature T_c for an assumed first-order chiral symmetry/deconfinement phase transition. The system is assumed to continue to expand at this fixed temperature, deriving the necessary energy from the latent heat of the transition. Eventually the quark-gluon plasma is entirely converted to hadronic matter. After this, the hadrons might maintain thermal contact for a while, as the matter continues to expand and cool. Finally, one estimates a ‘freeze-out’ temperature T_f at which the hadrons lose thermal contact with each other. Then they begin free-streaming towards the detectors. One adds to the Drell-Yan contribution the emission over the cooling curve, from T_0 to T_f , using equations of state for quark-gluon plasma and hadronic gas. This is the way in which the dilepton mass spectrum was computed in ref. [10], for example.

2.1 The rates for dilepton production from the QGP and hot mesons

Dileptons are normally assumed to be produced via the reaction $q\bar{q} \rightarrow l^+l^-$ in the plasma phase and $\pi^+\pi^- \rightarrow l^+l^-$ in the hadron phase. In the QCD sector we shall ignore corrections to the Born term. Those effects, and their consequence on M_T scaling are worthy of interest. Thus, at this level of approximation, the corresponding rate for production of dileptons having an

invariant mass M from the QGP phase is known to be given by

$$\frac{dN}{d^4x dM^2} = \frac{\sigma_q(M)}{2 (2\pi)^4} M^3 T K_1(M/T) \left[1 - \frac{4m_q^2}{M^2} \right], \quad (1)$$

where m_q is the mass of the quarks undergoing annihilation,

$$\sigma_q(M) = \frac{4\pi}{3} \frac{\alpha^2}{M^2} \left[1 + \frac{2m_l^2}{M^2} \right] \left[1 - \frac{4m_l^2}{M^2} \right]^{1/2} F_q(M) \quad (2)$$

and,

$$F_q(M) = N_c (2s + 1) \sum_f e_f^2 = \frac{24}{3} \quad (3)$$

for the QGP consisting of u, d, and s quarks. In the above, m_l is the mass of the leptons, α is the electromagnetic fine structure constant and N_c is a color factor. The quark and lepton masses will ultimately be set to zero.

The corresponding rate for pionic annihilation is obtained by replacing m_q by m_π in Eq. (1) and further taking the pionic form-factor F_π in place of F_q in Eq. (2). For the pion electromagnetic form factor we use a recent parametrization of Biagini et al. [11].

We have already indicated that the rates of dilepton yielding processes in a hot meson gas have recently been computed [7] by taking a complete set of light mesons and including decays and two-body reactions. Because of phase space arguments, these contributions should be dominant. The light pseudoscalar (P) and vector (V) mesons we included consist of π , η , ρ , ω , η' , ϕ , K , and K^* . Below the $\pi a_1 \rightarrow e^+e^-$ threshold, we have considered the decays $\rho \rightarrow \pi e^+e^-$, $K^{*\pm} \rightarrow K^\pm e^+e^-$, $K^{*0}(\bar{K}^{*0}) \rightarrow K^0(\bar{K}^0)e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\rho^0 \rightarrow \eta e^+e^-$, $\eta' \rightarrow \rho^0 e^+e^-$, $\eta' \rightarrow \omega e^+e^-$, $\phi \rightarrow \eta e^+e^-$,

$\phi \rightarrow \eta' e^+ e^-$, $\phi \rightarrow \pi^0 e^+ e^-$. We include all possible reactions of the type $P + P \rightarrow e^+ e^-$ and $V + V \rightarrow e^+ e^-$. The $V + P$ initial states considered are $\omega \pi^0$, $\rho \pi$, $\phi \pi^0$, $\omega \eta$, $\phi \eta$, $\rho^0 \eta$, $\omega \eta'$, $\phi \eta'$, $\rho \eta'$, $\bar{K}^* K$ and $K^* \bar{K}$. Furthermore, the effect of the a_1 meson has been discussed in connection with real photon emission [12, 13]. We have added the rates corresponding to the initial states πa_1 and $a_1 a_1$ into electron-positron pairs. The formalism to calculate all the Feynman amplitudes above is that of effective chiral Lagrangian models [7, 14]. Ref. [7] contains a complete analysis of the relative contribution of the processes we have included. The reader will also find there a discussion of how our Lagrangian parameters have been adjusted to reproduce experimental data and of form factor issues.

We have found that the net rate obtained by summing all the processes scales as $TK_1(M/T)$ to a high degree of accuracy between $M=0.3$ GeV, and 3 GeV. This is because of the fact that the majority of reactions considered in Ref. [7] share the pion electromagnetic form factor. In order to see this most clearly, we have plotted in Fig. 1 the effective form-factor obtained by summing all the channels enumerated above as,

$$\frac{dN}{d^4x dM^2} = \frac{\sigma_{\text{eff}}(M)}{2 (2\pi)^4} M^3 TK_1(M/T) \left[1 - \frac{4m_\pi^2}{M^2} \right] \quad (4)$$

with

$$\sigma_{\text{eff}}(M) = \frac{4\pi}{3} \frac{\alpha^2}{M^2} \left[1 + \frac{2m_l^2}{M^2} \right] \left[1 - \frac{4m_l^2}{M^2} \right]^{1/2} F_{\text{eff}}(M) \quad (5)$$

at temperatures of 100, 150, and 200 MeV. The scaling with $TK_1(M/T)$ mentioned above is seen to be satisfied over a reasonable range of invariant

mass. The deviation seen at very low-masses has its origin in the contributions $\omega \rightarrow \pi^0 l \bar{l}$, $\rho \rightarrow \pi l \bar{l}$, and $\phi \rightarrow \pi^0 l \bar{l}$, which however are only marginal for large invariant masses. There is a small breaking of our scaling hypothesis above $M = 2.5$ GeV because of the $a_1 a_1 \rightarrow e^+ e^-$ threshold. We have also shown for comparison the form-factors for the pionic annihilation and the annihilation of quarks. It is seen that if only pionic annihilation processes are included, the quark annihilation processes will dominate the spectra beyond $M \approx 1.5$ GeV, by two orders of magnitude. However, a proper accounting of all the mesons present in the hot hadronic matter makes the identification of the quark–gluon signal considerably more difficult; we shall return to this point later.

2.2 The dilepton distributions

2.2.1 Results for transverse-mass distributions

The simplest space-time evolution dynamics is provided by the longitudinal hydrodynamic expansion model of Bjorken [1]. However after the proper time $\approx R/c_s$, where R is the transverse dimension of the system and c_s is the speed of sound, the rarefaction wave-front from the surface will reach the centre and the transverse expansion [9] of the system can not be ignored. The transverse velocity of the fluid elements would increase monotonically if there is no change in equation of state. However, a first order phase transition, as in the case of quark-gluon plasma, slows down the transverse expansion of the system considerably.

We have considered head-on collision of two gold nuclei, and used the

criterion

$$T_0^3 \tau_0 = \frac{2\pi^4}{45\zeta(3)\pi R^2 4a_Q} \frac{dN}{dy_\pi} \left[f_0 + \frac{1-f_0}{r} \right] \quad (6)$$

to relate initial temperature (T_0) and the time (τ_0) to the pion rapidity density (dN/dy_π). In the above, $f_0=0$ gives the fraction of the QGP at the initial time, and we have taken $a_Q = 47.5\pi^2/90$ for a system consisting of u, d, and s quarks. The fraction $f_0 = 0$ when $T_i < T_c$, $0 \leq f_0 \leq 1$ when $T_i = T_c$, and $f_0 = 1$ when $T_i > T_c$. Furthermore, r , the ratio of degrees of freedom between the QGP phase and the hadronic phases is $47.5/6.8$, which corresponds to hadronic matter having the complete set of light mesons $\pi, \rho, \omega, \eta, \eta', \phi, K, K^*$, and a_1 [7]. As the immediate purpose of this work is to examine the relevance of M_T scaling, we shall use Bjorken's hydrodynamic expansion model in the following. Now the volume element in Bjorken hydrodynamics is given by,

$$d^4x = d^2x_T dz dt = \pi R^2 dy \tau d\tau \quad (7)$$

In order to see the so-called scaling behaviour of the M_T spectra, we first consider a case with $T_0 = 250$ MeV and $\tau_0 = 1$ fm/c. With those values, the system is initially in the QGP phase during the proper time from τ_0 to $\tau_q = (T_0/T_c)^3 \tau_0$, in the mixed-phase during τ_q to $\tau_h = r\tau_q$, and in the hadronic phase during τ_h to $\tau_f = (T_c/T_f)^3 \tau_h$, beyond which it undergoes freeze-out. We have taken the critical and freeze-out temperatures as 160 MeV and 120 MeV, respectively.

Now the number of dilepton pairs having an invariant mass M and transverse momentum p_T , so that $M_T = \sqrt{p_T^2 + M^2}$, can be written as (see [10])

for comparison),

$$\begin{aligned}
\frac{dN}{dM^2 dM_T dy} = & \frac{\sigma_q(M) M^2 M_T}{4(2\pi)^4} \left[1 - \frac{4m_q^2}{M^2} \right] \pi R^2 3T_0^6 \tau_0^2 M_T^{-6} [G(M_T/T_0) - G(M_T/T_c)] \\
& + \frac{\sigma_q(M) M^2 M_T}{4(2\pi)^4} \left[1 - \frac{4m_q^2}{M^2} \right] \frac{1}{2} (r-1) \tau_q^2 \pi R^2 K_0(M_T/T_c) \\
& + \frac{\sigma_{\text{eff}}(M) M^2 M_T}{4(2\pi)^4} \left[1 - \frac{4m_\pi^2}{M^2} \right] \frac{1}{2} r(r-1) \tau_q^2 \pi R^2 K_0(M_T/T_c) \\
& + \frac{\sigma_{\text{eff}}(M) M^2 M_T}{4(2\pi)^4} \left[1 - \frac{4m_\pi^2}{M^2} \right] \pi R^2 3T_c^6 \tau_h^2 M_T^{-6} [G(M_T/T_c) - G(M_T/T_f)] ,
\end{aligned} \tag{8}$$

where

$$G(z) = z^3(8 + z^2)K_3(z) . \tag{9}$$

In Fig. 2 we have plotted the results for the transverse mass distribution of dileptons for a fixed $M_T = 2.6$ GeV [8], against p_T . Note that this way of plotting is convenient: if the scaling holds this plot will be a straight horizontal line. We show results obtained when only the pionic annihilation process is included for the hadronic matter, and when the entire spectrum of hadronic processes leading to dileptons are considered. If we restrict our analysis to the pion-pion process, the total contribution obtained by summing up the quark matter and hadronic matter signals will exhibit scaling. However, taking account of all the processes in the hadronic matter leads to a considerable enhancement of dilepton production even up to an invariant mass of 2 GeV (lower values of p_T on this figure) [7]. No scaling of the M_T spectra will be seen as the QGP contribution, which itself scales with p_T for the case of no transverse expansion, is only a small fraction of the total

contribution. In this sense, the apparent flatness below $p_T = 1.5$ GeV/c is accidental and not a reflection of the QCD M_T scaling. The bulk of the signal is from the hadronic sector, where the hadronic electromagnetic form factors break the scaling. It should also be remembered that, even if the lifetime of the QGP is large, as it would be in the case of a higher initial temperature, the transverse velocity of the fluid could then be substantial even during the QGP phase which would furthermore offset the M_T scaling property even for the QGP contribution.

Thus we conclude that the M_T scaling of the dilepton spectra, which has been proposed as a signature of the presence of quark-matter, does not hold at the temperatures considered in this work, once a more complete description of dilepton-yielding processes is achieved. We do not display in this work the M_T feature of the Drell-Yan dileptons. We shall return to this point in the discussion.

2.2.2 The invariant mass distribution

The invariant mass distribution of dileptons provides a very useful parametrization of the data, as they are relatively less affected by the models for space-time evolution. The final results are easily written for the initial state in QGP as,

$$\begin{aligned} \frac{dN}{dM^2 dy} = & \frac{\sigma_q(M)}{2(2\pi)^4} M^3 \left[1 - \frac{4m_q^2}{M^2} \right] \pi R^2 3T_0^6 \tau_0^2 M^{-5} [H(M/T_0) - H(M/T_c)] \\ & + \frac{\sigma_q(M)}{2(2\pi)^4} M^3 \left[1 - \frac{4m_q^2}{M^2} \right] \pi R^2 \frac{1}{2} (r-1) \tau_0^2 T_c K_1(M/T_c) \end{aligned}$$

$$\begin{aligned}
& + \frac{\sigma_{\text{eff}}(M)}{2(2\pi)^4} M^3 \left[1 - \frac{4m_\pi^2}{M^2} \right] \pi R^2 \frac{1}{2} r(r-1) \tau_0^2 T_c K_1(M/T_c) \\
& + \frac{\sigma_{\text{eff}}(M)}{2(2\pi)^4} M^3 \left[1 - \frac{4m_\pi^2}{M^2} \right] \pi R^2 3T_c^6 \tau_c^2 M^{-5} [H(M/T_c) - H(M/T_f)] ,
\end{aligned} \tag{10}$$

where

$$H(z) = z^2(8 + z^2)K_0(z) + 4z(4 + z^2)K_1(z) . \tag{11}$$

We plot in Fig. 3 the mass spectrum for the same $\{\tau_0, T_0\}$ initial conditions as in the previous section. We have also shown the Drell-Yan spectrum for collision of two lead nuclei at $\sqrt{s} = 200A$ GeV, with structure functions obtained from the set I of Duke and Owens[15]. It is clear from this figure that our thermal QCD signal has little or no chance of shining through the hadron gas and Drell-Yan “backgrounds”. Then, for a somewhat extreme viewpoint, we have also plotted the invariant mass spectrum for dileptons, taking initial temperature T_0 as 500 MeV and the initial time $\tau_0 = 1/3T_0$, appropriate for energies reached at RHIC for collisions involving two gold nuclei [16]. Looking at Fig. 4, we immediately realize that the invariant mass window for seeing the emissions from the QGP are pushed to beyond 2 GeV, once the full spectrum of dilepton yielding reactions is included. We note the discomfoting feature that, even at such temperatures, the emissions from the QGP are neither much larger than the Drell-Yan contribution, nor are they significantly larger than the emissions from the hadronic matter. This demands a very careful analysis of the dilepton spectra before it can be used as a signature of QGP at RHIC energies. We do not plot the M_T scaling

features of our solution with this high initial temperature: there, transverse expansion effects could certainly not be ignored. The transverse expansion influence on the net invariant mass spectrum also needs to be computed, as it will shorten the lifetime of the hadronic and mixed phases [17].

3 Discussion

We have addressed in this paper the issue of the proposed M_T scaling of the dilepton spectrum in high energy heavy ion collisions. We have found that the integrated lepton pair distributions would not keep any memory of the M_T scaling properties of the original plasma phase. This is because of the sheer size of the hadronic gas signal, and because the scaling hypothesis is violated strongly in the nonperturbative sector, owing to the structure of the timelike electromagnetic form factors. Of course, any calculation such as ours is an approximate one. However, we believe that the approximations we have made would have made the scaling easier to observe.

Firstly, we have not attempted a quantitative calculation of transverse flow stemming from hydrodynamic effects. To reiterate, any flow features will spoil the scaling properties. If the quark–gluon signal is helped by dialing a high initial temperature in our calculations, this indicates (i) a somewhat longer lived QCD phase where flow will develop on its own and, (ii) the importance of the relaxation mechanisms. This brings us to our second point. In our transverse mass spectra we have neglected the Drell–Yan signal. It is easy to verify using simple expressions that the Drell–Yan signal violates

M_T scaling. This is easily understood, as one of the premises for scaling is thermal equilibrium. However, the simple Drell–Yan calculations might not be so relevant for the high energy collisions of heavy nuclei if the original parton distribution is modified during a nucleus–nucleus collisions. Such effects could surely modify the Drell–Yan estimates. Perhaps an adequate attempt to consider parton rescattering effects is provided by the Parton Cascade Model (PCM) [2]. In this picture, the partons start in a completely nonequilibrium state and they are subsequently driven towards relaxation by continuous processes. In the PCM, the M_T scaling features have been analyzed [18]. The result there is that the scaling hypothesis is also strongly violated, even at the parton level. This state of affairs may owe to several facts. Among others, they are the lack of thermal and chemical equilibration, and the existence of additional scales in the problem, provided by infrared cutoff parameters and higher order QCD corrections. Also, processes that do not scale may also contribute [19]. Combining the above considerations with our own results, we are forced to the somewhat pessimistic conclusion that there is little hope that the observed lepton pair spectrum could show any evidence of “genuine” scaling. Conversely, any flatness in the transverse mass spectrum, plotted against transverse momentum, could not be interpreted unambiguously as a relic of a deconfined QCD phase.

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Figure captions

Fig. 1 The effective form-factor for dilepton yielding processes in hadronic matter when the rates obtained in Ref. [7] are written as Eq. (2.4). The dashed-dotted, dashed and solid curves represent the effective form-factor for $T=150, 200$ and 250 MeV, respectively. The tight-dotted curve is the form-factor for pionic annihilation from Biagini et al. [11]. The loose-dotted curve represents the quark-antiquark “form factor”.

Fig. 2 Transverse-mass spectra for dileptons, for contributions from quark-annihilation (horizontal dashed line), from the full set of mesons (dashed-dotted curve), and from the pion gas approximation (solid curve). The temperature is 250 MeV and $\tau_0 = 1$ fm/c. The transverse mass is fixed at $M_T = 2.6$ GeV [8].

Fig. 3 Dilepton mass spectra. We show the contributions from quark-matter (dashed line), pion annihilation (dotted curve), Drell-Yan (dashed-dotted curve) processes and from all the hadronic processes considered in Ref. [7] (solid curve). The temperature and formation time are the same as in the previous figure.

Fig. 4 Same caption as in Fig. 3, but for $T_0 = 500$ MeV and $\tau_0 = 1/3T_0$.

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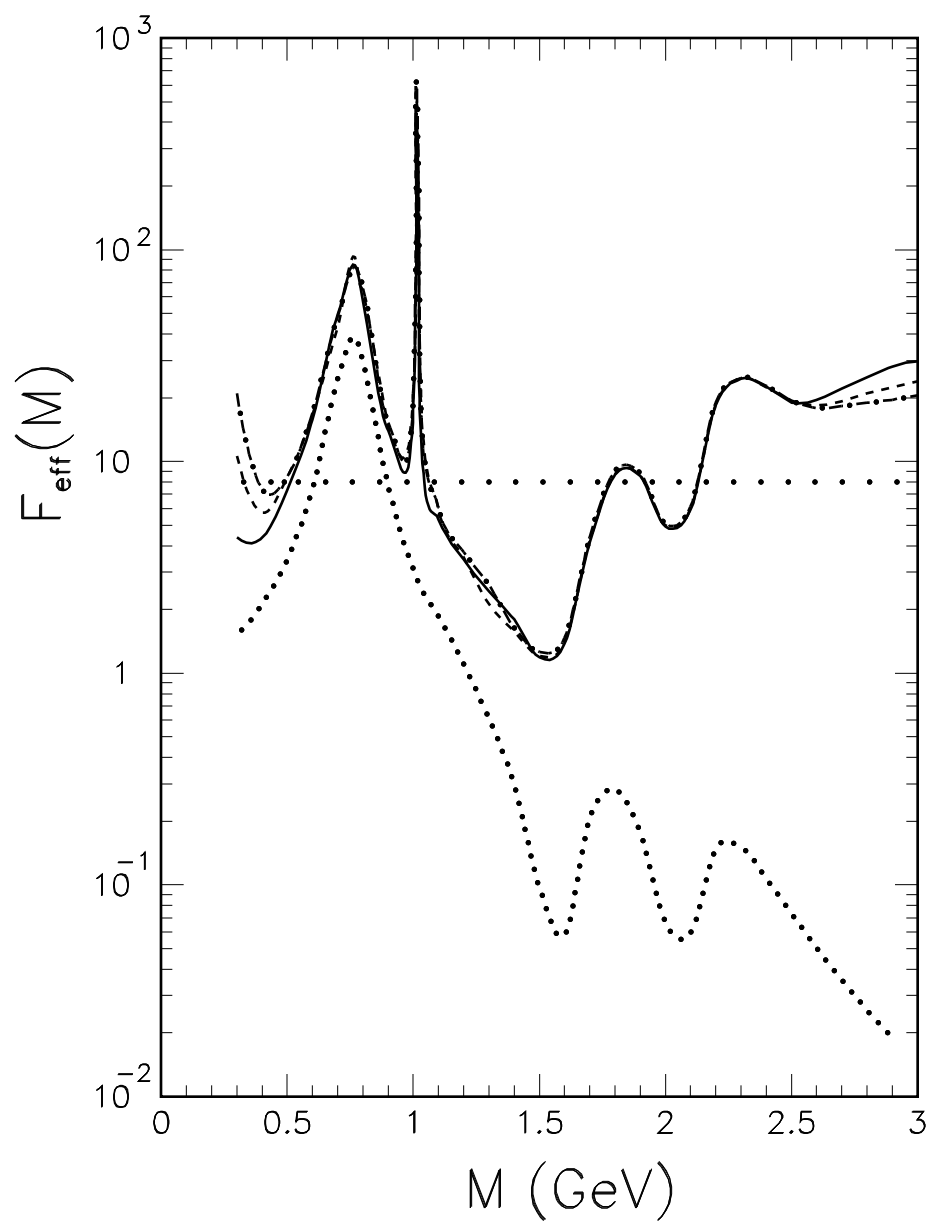


Fig. 1

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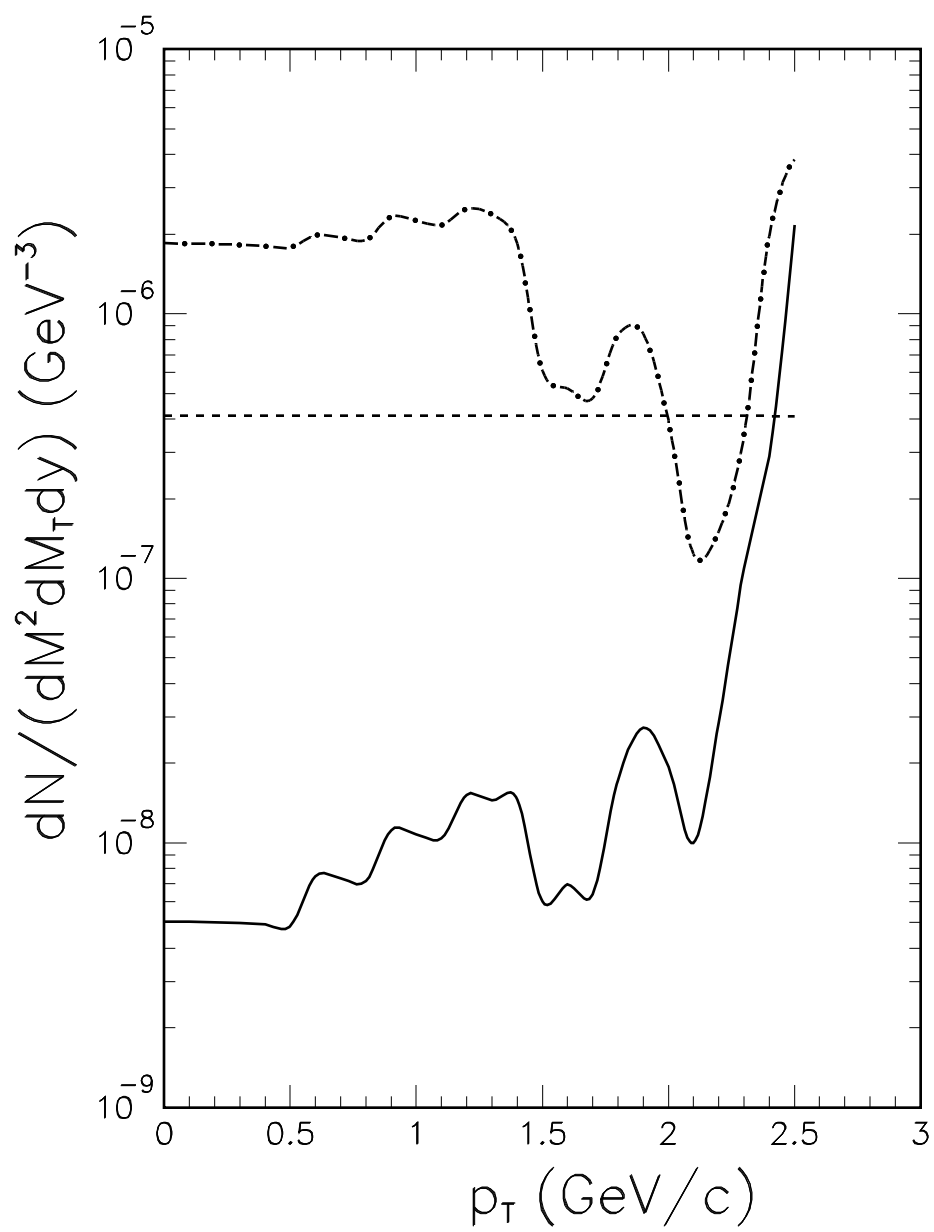


Fig. 2

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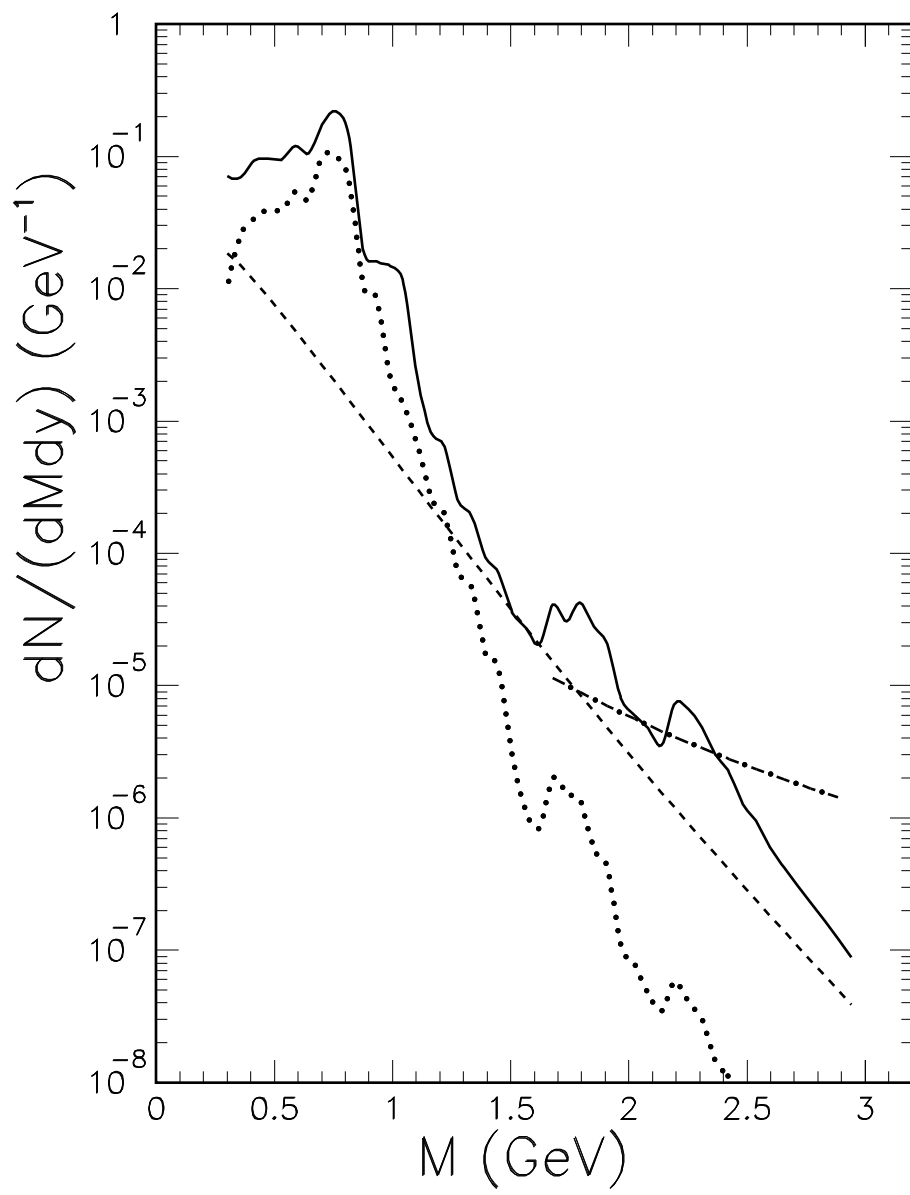


Fig. 3

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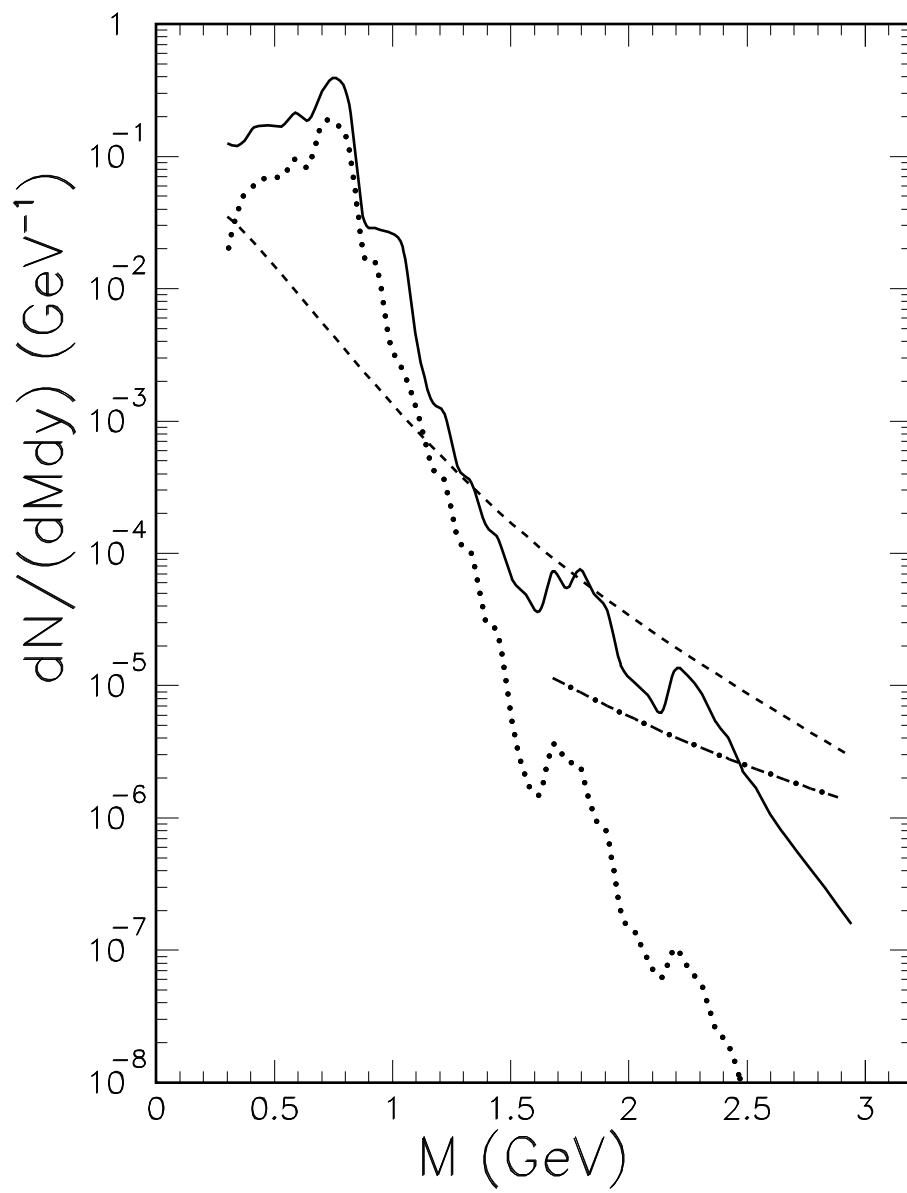


Fig. 4